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Bleaching efficacy of in-office bleaching with violet light using low-concentration hydrogen peroxide nanoparticulate photocatalyst gel: A randomized controlled trial

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ABSTRACT

Objective: This randomized controlled trial aimed to evaluate the bleaching efficacy and tooth sensitivity (TS) of participants submitted to different application protocols of in-office bleaching with violet light using 6 % hydrogen peroxide (HP) nanoparticulate photocatalyst gel.

Materials and methods: Sixty-six participants were randomized and bleached using either a 6 % HP (Nano White, DMC), and/or violet light (Bright Max Whitening, MMOptics), according to the following protocols: 1) only violet light (VIOL); 2) only bleaching gel application (BG) and; 3) combined bleaching gel application + violet light (BG+VIOL). The bleaching efficacy was evaluated with the Vita Easyshade spectrophotometer, Vita Classical and Vita Bleachedguide scales. The risk and intensity of TS were recorded using a 0–10 visual analogue scale (VAS) and a 0–4 numerical scale (NRS). Color change and intensity of TS values were compared using one-way ANOVA and Tukey's test were used. The absolute risk of TS was compared using the Chi-square test ($\alpha = 0.05$).

Results: A significant and higher degree of bleaching was observed in the BG and BG+VIOL groups compared to the VIOL group ($p < 0.003$). Despite no significant differences in the risk ($p > 0.07$) and intensity ($p > 0.28$) of TS among groups, a higher risk of TS was observed in the BG and BG+VIOL groups.

Conclusions: Using VIOL reduced the risk of TS but did not improve bleaching. However, BG+VIOL with low-concentration HP nanoparticulate photocatalyst gel achieved equal efficacy and was less likely to cause TS compared to BG.

1. Introduction

In-office dental bleaching has become popular due to visible results often seen immediately after the first session [1]. Generally, the protocol includes retracting the soft tissues and protecting the gingival tissue with a light-cured barrier [1,2]. After protecting the patient, high concentrations of hydrogen peroxide (HP) [30–40 %] in gel form are applied to the buccal tooth surfaces. The bleaching gel, typically peroxide-based, does not remain confined to the enamel surface [3]. It, along with its free radicals, penetrates the dental structure and interacts with underlying tissues, producing the whitening effect desired by patients [3]. However, the bleaching agent is not restricted to the hard tissues alone [3,4]. Due to its permeability, it can reach the dental pulp [3,4], potentially causing inflammatory responses [5]. This reaction leads to the most reported adverse effect in both clinical studies and practice: tooth sensitivity (TS) [6,7].

One of the alternatives to reduce TS is the use of lower concentrations of HP, specifically 6 % [8–12]. This technique has gained prominence [8], particularly among patients with pre-existing dentin hypersensitivity and younger patients who prefer in-office bleaching

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over at-home treatment with customized trays. A closer examination of randomized clinical trial evaluating 6 % HP has shown that it is not as effective as higher concentrations [9–11,13], potentially requiring more sessions to achieve the desired results.

Light-assisted bleaching, especially with blue light, was very popular in the past [14–16]. However, due to substantial evidence indicating the low efficacy of light-assisted bleaching associated when compared to bleaching gels alone [14–16], its use has declined. Despite this, light-assisted bleaching remains attractive to patients and professionals. Therefore, new light sources, such as violet light, have been introduced to improve bleaching efficacy [17].

Initially, violet light was proposed for use without any bleaching agents [9,18–23]. However, the effectiveness of violet light alone as a whitening method remains a subject of ongoing debate in the literature. Some studies indicate that violet light can produce a whitening effect [22–24], while others do not support this conclusion [19,20]. As a result, the combined application of bleaching gel with violet light irradiation has gained popularity [9,18,19,21,22]. Nevertheless, the outcomes associated with this technique are still controversial in the existing literature. The latest innovation in this area involves doping gels to enhance photocatalysis [25–33]. Photocatalysis refers to the process in which light energy activates a chemical reaction, in this case, the breakdown of HP. This is significant because the release of radicals—specifically reactive oxygen species (ROS), such as hydroxyl radicals (•OH), hydroperoxyl radicals (•OOH−), and superoxide anions (O_2•−) plays a crucial role in the bleaching process [3]. These radicals are highly reactive and interact with the organic molecules present in the dental structures, converting them into simpler structures or altering their optical properties, resulting in the desired whitening effect [3].

The incorporation of co-doped nanoparticles into the gels enhances the generation and longevity of these ROS [25–33]. This prolonged release of radicals ensures sustained interaction with the organic components of the dental structure, making the color change more efficient while potentially reducing pulp permeability. As a result, these advanced gels are expected to cause less TS, as the reduced amount of unreacted HP lowers cytotoxicity risks [25–33].

While numerous studies provide valuable insights into the potential of in-office dental bleaching using lower-concentration HP products containing nanoparticles [25–33], there are few clinical studies assessing the effectiveness of nanoparticles in conjunction with low-concentration HP products [9]. In fact, only one clinical study evaluated this combination (low-concentrated HP + violet light) [9], but it faced limitations, including a small sample size, which may lead to observed events being attributed to chance rather than the intervention's effect [9]. Results that appear clinically significant may indeed reflect this small sample size and may not be replicable in larger studies. Furthermore, the 25 % dropout rate during evaluations introduces a substantial risk of bias, particularly if the reasons for dropout are related to the outcomes, such as TS or lack of efficacy. These factors compromise both the internal and external validity of the study, reducing the reliability of the results and raising concerns about potential bias [9]. Thus, the use of low-concentration gels containing these nanoparticles, combined with violet light, can achieve superior aesthetic outcomes while minimizing adverse effects such as TS during in-office dental bleaching.

Although in vitro studies lay the groundwork for scientific understanding, they are insufficient to substantiate clinical recommendations on their own. Only well-designed clinical studies can provide the robust evidence necessary to support these recommendations and ensure the safety and efficacy of these innovative bleaching products in a clinical setting. Therefore, this randomized controlled trial aimed to evaluate the bleaching efficacy and TS of participants submitted to the use of low-concentration HP nanoparticulate photocatalyst gel or violet light, either alone or in combination. We tested as a primary research hypothesis whether (1) the use of low-concentration HP nanoparticulate photocatalyst gel or violet light, either alone or in combination will be no different in terms of color change. Additionally, we tested, as secondary hypotheses, that the use of low-concentration HP nanoparticulate photocatalyst gel or violet light, either alone or in combination will differ in terms of (2) absolute risks and intensities of TS.

2. Material and methods

2.1. Study design, settings, location of data collection, and recruitment

The study was approved by the Ethics Committee of the CEUMA University (Sao Luis, MA, Brazil; approval number: 6.159.611) and was registered a priori in the Brazilian Registry of Clinical Trials (https://ensaiosclinicos.gov.br) under the registration number RBR-3q2gvd. The report adheres to the Consolidated Standards of Reporting Trials guidelines [34,35]. This study was design as a parallel, evaluator-blinded randomized controlled trial with an equal allocation ratio. It was conducted at the CEUMA University (Sao Luis, MA, Brazil), with data collected at its Dental Clinics from January 2024 to April 2024. Recruitment involved placing written advertisements on the university walls and utilizing social media to obtain a convenient sample. Before inclusion in the study, participants were required to read and sign the informed consent form.

2.2. Eligibility criteria

To be eligible for the study, participants had to meet the following criteria: good general and oral health, be over 18 years old, and have no periodontal disease, gingival recession, or carious lesions in the anterior teeth. Additionally, their upper central incisors had to have a color of A2 or darker, as determined by the value-oriented shade guide (Vita Classical B1-C4, Vita Zahnfabrik, Bad Säckingen, Germany). Exclusion criteria included a history of prior bleaching, dentin hypersensitivity, current use of orthodontic appliances, dental prostheses or restorations in the anterior teeth, previous endodontic treatment of anterior teeth, severe tooth discoloration (e.g., fluorosis, pulpless teeth, or stains from tetracycline use), visible cracks in teeth, ongoing use of medications such as analgesics and anti-inflammatories, pregnancy or lactation, and habits such as smoking or bruxism.

2.3. Sample size estimation

In this clinical trial, the primary outcome for sample size estimation was the objective color change measured in ΔE_{00}. In a pilot study involving 10 participants (data not shown), the observed ΔE_{00} value after 30-min application of a 6 % HP gel (Nano White, DMC) across two bleaching sessions was 3.7 ± 2.1. Using a 50:50 % acceptability limit of 1.8 [36], it was determined that 22 volunteers per group (66 volunteers in total) were necessary to ensure an 80 % certainty of excluding a mean difference greater than 1.8 between the standard treatment (only bleaching gel application) and the experimental treatments (only violet light application or combined bleaching gel + violet light application) (www.sealedenvelope.com).

2.4. Random sequence generation and allocation concealment

Randomization in blocks of 3 and 6 was carried out with an equal allocation ratio. The randomization process was conducted using a freely available web-based software (www.sealedenvelope.com). The patients were randomly assigned to one of three groups (n = 22) according to the in-office bleaching protocol: (1) combined bleaching gel application for 30 min plus 20 applications of violet light, each lasting 1 min with a 30-second pause between applications; (2) violet light only, with 20 applications of 1 min each with a 30-second pause between applications; and (3) bleaching gel application only, for 30 min.

The allocation sequence was determined using opaque, sealed, and sequentially numbered envelopes. The individual responsible for randomization and blinding was not involved in the intervention process. Before the bleaching procedure, the operator opened the envelope containing the randomization details, thereby revealing the participant's assigned group. This process ensured proper concealment of the allocation until the intervention.

2.5. Blinding

Only the evaluators were blinded in this study, classifying it as a single-blind clinical trial. Both the operator and the patients were aware of the group assignments due to the distinct differences in the interventions between the groups, which made it impossible to blind these individuals. This limitation is common in trials where visible or procedural differences are integral to the treatment protocols.

2.6. Study intervention

The bleaching procedure was carried out by two dentists with over 5 years of clinical experience. Before the procedure, participants underwent dental prophylaxis using pumice stone (SS White, Rio de Janeiro, RJ, Brazil) and water with a Robinson brush at low speed (All Prime, São José, SC, Brazil). A soft tissue retractor (Arcflex, FGM Dental Products, Joinville, SC, Brazil) was used to retract the lips and cheeks, while a light-cured gingival barrier (Nano White, DMC Equip., São Carlos, SP, Brazil) was applied to protect the gingival tissues. The barrier was light-cured for 30 s per tooth (Valo, Ultradent, Salt Lake, UT, USA). According to the randomization, participants were allocated to one of the following groups:

2.6.1. Group receiving only violet light (VIOL)

The violet light source (Bright Max Whitening, MMOptics, São Carlos, SP, Brazil) has 1.2 W power, produced by four violet LED emitters (300 mW each) with a wavelength of 405–410 nm [37]. The distance of 8 mm was considered for calculating the power density (power density of 112 mW/cm^2), target area of 10.7 cm^2, energy density of 134 J/cm^2, and total energy/session of 1440 J [37]. Both dental arches, from the second premolar to the second premolar on each side, were subjected to the bleaching procedure. The complete violet light irradiation cycle lasted 30 min, consisting of twenty 1-min irradiations with consecutive 30-second intervals. The violet light device was kept at a distance of 8 mm from the arches during the entire process. In the intervals between irradiations, the teeth were kept hydrated using moist gauze. After the procedure, the gingival barrier was removed, and the teeth were thoroughly cleaned with an air-water spray. Each participant underwent two bleaching sessions, with a 7-day interval between sessions.

2.6.2. Group receiving only bleaching gel (BG)

The 6 % HP nanoparticulate photocatalyst gel (DMC Equip., São Carlos, SP, Brazil) was provided in pre-dosed attachable syringes. To activate the gel, the HP syringe and the thickener syringe were connected using a luer lock connector. The plungers were pressed 14 to 15 times to ensure thorough mixing, producing a fully activated white gel. The mixture was then transferred entirely into one syringe, which was disconnected before attaching an application tip. The gel was applied evenly to the buccal surfaces of the participants' teeth and left undisturbed for 30 min. After the bleaching protocol, the gel was carefully removed using an aspirator cannula and a moistened gauze [6,7,12].

Unfortunately, the exact composition of the dopant in the gel used in this study is unknown. The gel's ingredients are classified as photocatalytic nanoparticles, and some literature suggests doping with TiO_N nanoparticles [10,38,39]. However, precise information is unavailable, as the manufacturers have not disclosed the specific details of the formulation.

2.6.3. Group receiving combined bleaching gel + violet light (BG+VIOL)

In this group, after the application of the bleaching product, the violet light device was utilized. Both the bleaching application and the violet light treatment adhered to the procedures previously described [19,20]. In the end of the bleaching protocol, gel was removed using an aspirator cannula and a moistened gauze.

For all groups, participants had both dental arches treated with tooth bleaching, extending from the second premolar to the second premolar on each side. At the conclusion of each treatment session, the gingival barrier was removed, and the patient's teeth were cleaned with an air-water spray. Each participant underwent two bleaching sessions, with a seven-day interval between them. Additionally, participants were instructed to maintain their oral hygiene by regularly brushing their teeth with fluoride toothpaste that did not contain desensitizing agents and to avoid using medications such as analgesics and anti-inflammatory drugs throughout the treatment period.

2.7. Color evaluation

The color assessment, both objective and subjective, was recorded before treatment, after the first and second bleaching sessions, and 30 days following the completion of treatment. Two blinded and calibrated evaluators, who demonstrated superior color discrimination competency according to ISO/TR 2,864,228 [40], assessed the color outcomes, ensuring an inter-examiner agreement level of at least 85 % (Kappa statistic). In the event of a disagreement during evaluations, the evaluators were required to reach a consensus before dismissing the participant. All assessments were conducted in the same room under consistent lighting conditions, with the participants' teeth properly hydrated.

The color assessment employed an objective method using the Vita Easyshade Advance 4.0 spectrophotometer (Vita Zahnfabrik, Bad Säckingen, Germany). This spectrophotometer operates based on the CIELab color space system, where L* represents the lightness value ranging from 0 (black) to 100 (white). Additionally, the a* value measures color along the green-red axis, while the b* value measures color along the blue-yellow axis. The device was calibrated prior to each measurement to ensure accuracy and reliability, providing these parameters during the color assessment. To ensure consistent and standardized measurement of objective color, an impression of the participants' upper arch was taken using gray condensation silicone (Zetaplus, Zhermack SpA, Rome, Italy) to create a guide for the upper anterior teeth. The matrix, formed in the buccal region of the middle third of the upper right central incisor, was perforated to align with the active tip of the Vita Easyshade Advance 4.0 spectrophotometer. This was accomplished using a 6 mm diameter circular scalpel (Biopsy Punch, Miltex, York, NJ, USA) [6,7,12].

The difference between the coordinate registered before, after the first and second bleaching sessions, and 30 days after the end of the treatment, were calculated using the following formulas: CIEDE $\Delta E_{00} = [(\Delta L/kLSL)^2 + (\Delta C/kCSC)^2 + (\Delta H/kHSH)^2 + RT\ (\Delta C^*\Delta H\ /SC^*SH)]^{1/2}$ [42]; and CIELab: $\Delta E_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$ [41]. The Whiteness Index for Dentistry (WI_D) was calculated using the formula: $WI_D = 0.551 \times L - 2.324 \times a - 1.1 \times b$ [43]. Additionally, changes in WI_D for each step were determined by subtracting the values observed at each assessment time from those calculated in the prior step (ΔWI_D). The 50:50 % perceptibility threshold were considered when the color differences observed before and after bleaching exceeded $\Delta E_{00} > 0.8$, $\Delta E_{ab} > 1.2$ [36] and $\Delta WI_D > 0.7$ [44], as well as the differences in means between the groups.

Additionally, color evaluation of the middle third of the upper right central incisor was performed using subjective methods with shade guides (Vita Classical A1-C4 and Vita Bleachedguide 3D-MASTER, both from Vita Zahnfabrik, Bad Säckingen, Germany). The value-oriented Vita Classical A1-C4 color scale consists of 16 color shade guides arranged from the highest (B1) to the lowest (C4) value. The Vita Bleachedguide 3D-MASTER scale is specifically designed for tooth bleaching and contains lighter-colored tabs, arranged from the highest value (0M1) to the lowest (5M3) value. The color change of the shade guide units (ΔSGU) in the middle third of the buccal surface of the right central incisors was calculated by subtracting the baseline color number from the final color number [6,7,12].

2.8. Tooth sensitivity (TS) evaluation

Participants were instructed to assess their TS using a five-point numerical rating scale (NRS) ranging from 0 (none) to 4 (severe) and a visual analogue scale (VAS) from 0 to 10, where 0 indicated no TS and 10 signified severe TS. The assessment of TS was defined as brief, acute discomfort that may persist for up to 48 h following the bleaching session. Participants were asked to mark a vertical line along the 0–10 cm VAS line to indicate the intensity of their TS. Assessments were conducted immediately after the bleaching procedure and at intervals of up to 1 hour, 24 h, and 48 h post-treatment. For the dichotomous assessment of TS risk, participants who recorded a value of zero were categorized as not experiencing TS, while all other recorded values indicated the presence of TS. To quantify the intensity of TS, the distance from the marked region on the VAS and NRS to the zero end was measured in centimeters. This assessment was conducted during both the first and second bleaching sessions and the worst value was selected for statistical analysis. The "worst scenario" refers to the highest level of perceived TS that each participant reported during the treatment [6,7,12].

2.9. Statistical analysis

The statistician was blinded to the study groups, ensuring objectivity in the analysis. All randomized participants were included, and the intent-to-treat protocol was followed. Statistical analysis began with the Kolmogorov-Smirnov test to evaluate normality, and the Bartlett test was employed to assess the equality of variances (data not reported). Cohen's kappa statistics were utilized to determine the agreement among examiners for the subjective measurement of bleaching efficacy. One-way ANOVA and Tukey's test were used to analyze color change, while the Chi-square test was applied to compare the absolute risk of TS. The intensity of TS measured by NRS was analyzed using the Kruskal-Wallis test due to the non-normal distribution of the data. On the other hand, the intensity of TS measured by VAS was analyzed using one-way ANOVA and Tukey's test. Statistical analyses were performed using SigmaPlot 14.0 software (Systat Software Inc., San Jose, CA, USA), with a significance level (alpha) set at 5 % for all tests.

3. RESULTS

3.1. Characteristics of included participants

One hundred one participants were examined, of which sixty-six were included in the clinical study (Fig. 1). Table 1 outlines the baseline characteristics of both the teeth and participants, highlighting the similarities among the groups. No participant loss was recorded during the study follow-up.

Table 1
Baseline characteristics of the participants, including age and gender.

	VIOL	BG	BG+VIOL
Baseline color (SGU; mean ± SD)*	5.3 ± 0.9	5.3 ± 1.1	5.9 ± 1.9
Baseline color (WI_D; mean ± SD)**	20.5 ± 2.7	21.2 ± 4.8	20.4 ± 5.5
Age (years; mean ± SD)	25.0 ± 5.3	22.3 ± 4.2	23.3 ± 4.9
Gender (female; %)***	27	41	54

* Abbreviations: SGU, shade guide unit measured by Vita Classical scale color evaluation.

** Abbreviations: WI_D, Whiteness Index for Dentistry baseline measured by Vita Easyshade spectrophotometer.

*** No significant differences were observed regarding gender (chi-square test; $p \geq 0.12$).

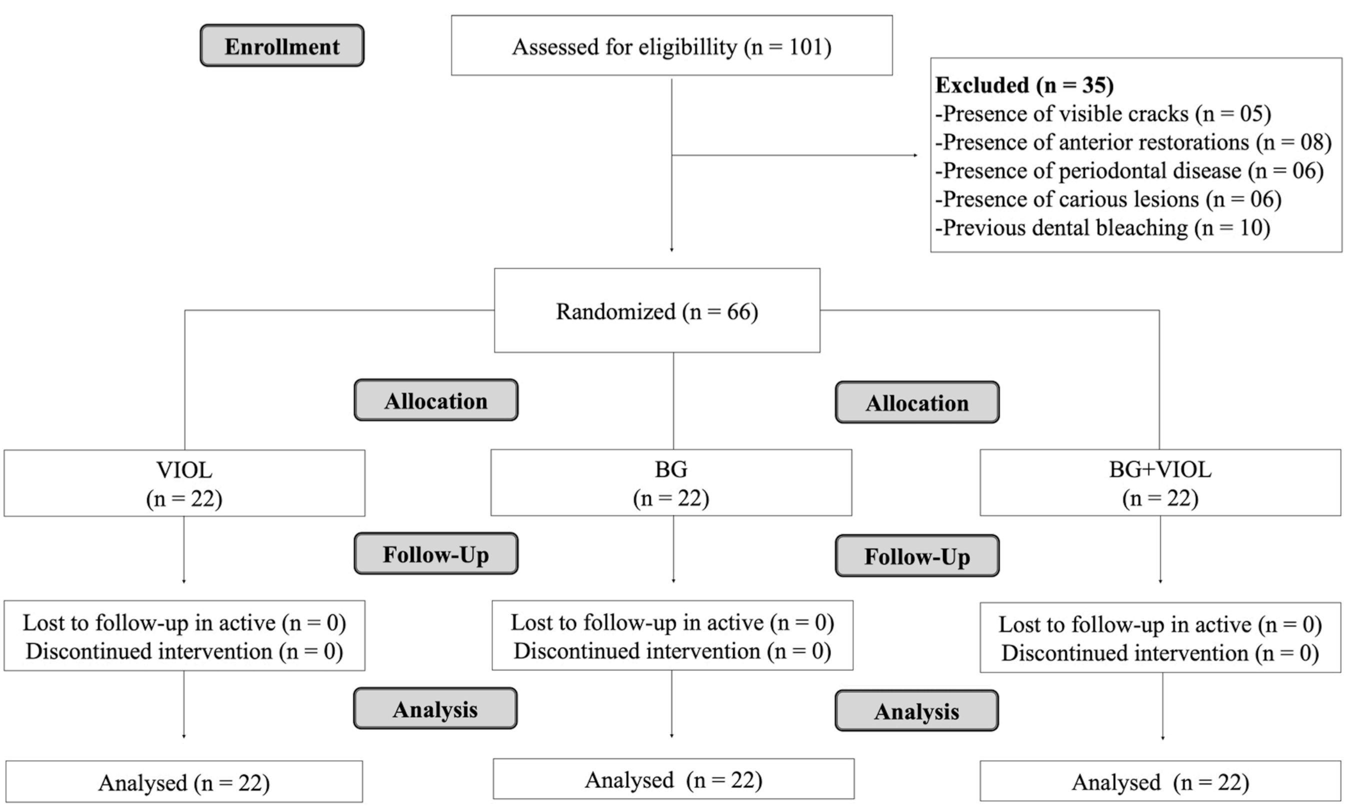

Fig. 1. CONSORT Flow Diagram.

3.2. Bleaching efficacy

The overall Cohen's kappa statistics (0.94 %) demonstrated a high level of agreement among the examiners regarding the main outcome subjective bleaching efficacy. The results of color change are presented in Table 2. When objectives measurements were evaluated, some similarities in color change were noted between the BG group and the VIOL group in terms of ΔE_{00} and ΔE_{ab} after one-week (Table 2). Usually, a significant and greater degree of bleaching was observed in the BG and BG+VIOL groups compared to the VIOL group (Table 2; $p < 0.003$), with no significant differences between the BG and BG+VIOL groups. Furthermore, when using the Vita Classical and Vita Bleachedguide guide scales to measure color change, significant differences were observed among the groups (Table 2; $p < 0.000001$), favoring the BG and BG+VIOL groups over the VIOL group, regardless of the assessment time.

Table 2
Means and standard deviations of color differences (ΔE_{ab}, ΔE_{00} and ΔWI_D) measured by Vita Easyshade) and shade guide units (ΔSGU) assessed using Vita Classical and Vita Bleachedguide 3D-MASTER at different time points.

Color change evaluation	Evaluation period	Groups			p-value*
		VIOL	BG	BG+VIOL	
ΔE_{00}	Baseline vs. 1st week	0.8 ± 1.2 B	1.9 ± 1.1 A,B	2.0 ± 0.7 A	0.0003
	Baseline vs. 2nd week	1.2 ± 1.2 B	3.1 ± 1.2 A	3.8 ± 1.1 A	<0.000001
	Baseline vs. 1-month	0.8 ± 1.3 B	2.5 ± 1.1 A	3.2 ± 0.9 A	<0.000001
ΔE_{ab}	Baseline vs. 1st week	1.2 ± 2.1 B	2.7 ± 1.8 A,B	3.0 ± 1.0A	0.001
	Baseline vs. 2nd week	1.7 ± 2.0 B	4.5 ± 1.8 A	5.6 ± 1.4 A	<0.000001
	Baseline vs. 1-month	1.2 ± 2.2 B	3.6 ± 1.7 A	4.8 ± 1.2 A	<0.000001
ΔWI_D	Baseline vs. 1st week	0.8 ± 2.7 B	4.5 ± 3.7 A	4.5 ± 2.1 A	<0.00003
	Baseline vs. 2nd week	1.6 ± 2.9 B	6.4 ± 2.3 A	8.7 ± 2.5 A	<0.000001
	Baseline vs. 1-month	0.7 ± 2.7 B	6.0 ± 3.9 A	7.0 ± 2.2 A	<0.000001
ΔSGU Vita Classical	Baseline vs. 1st week	0.1 ± 0.3 B	1.6 ± 1.1 A	1.6 ± 1.3 A	<0.000001
	Baseline vs. 2nd week	0.5 ± 0.9 B	2.3 ± 1.4 A	2.4 ± 1.6 A	<0.000001
	Baseline vs. 1-month	0.5 ± 0.8 B	2.4 ± 1.4 A	2.4 ± 1.6 A	<0.000001
ΔSGU Bleachedguide	Baseline vs. 1st week	0.1 ± 0.5 B	2.0 ± 1.3 A	1.5 ± 1.3 A	<0.000001
	Baseline vs. 2nd week	0.7 ± 1.0 B	3.9 ± 2.5 A	3.1 ± 2.1 A	<0.000001
	Baseline vs. 1-month	0.7 ± 1.0 B	3.9 ± 2.2 A	3.1 ± 1.9 A	<0.000001

* One-way ANOVA (similar letters in each line means no significant differences between groups).

3.3. Tooth sensitivity (TS)

The absolute risk of TS was 36 % (95 % CI 19 % to 57 %) for the BG+VIOL group, 32 % (95 % CI 16 % to 53 %) for the VIOL group, and 63 % (95 % CI 42 % to 80 %) for the BG group (Table 3). No statistically significant differences were observed when comparing the three groups (Table 3; $p > 0.13$).

Regarding the intensity of TS, statistical analysis revealed no significant differences among the groups in the worst-case scenario for both the NRS ($p > 0.28$) and VAS ($p > 0.49$). Overall, the intensity of TS remained mild throughout the assessment period for all evaluated groups (Table 4).

4. Discussion

Bleaching gels containing nanoparticles photocatalyst compounds, designed to accelerate in-office dental bleaching when associated with violet light, were considered a significant innovation in the field [25–33]. Several studies have demonstrated the in vitro benefits of doping in improving bleaching efficacy [25–33]. However, there are limited studies evaluating the gel used in the present study, with most research focusing on new and experimental doping's.

In vitro studies are essential for scientific progress; however, robust, well-planned, and well-delineated clinical studies can serve as reliable clinical indicators. The number of articles that clinically evaluate doped gels, especially at low concentrations, is limited [9].

Bleaching efficacy was observed in the groups using bleaching gels, either alone or in combination with violet light. This outcome was expected, as the bleaching gel contains HP, which penetrates the dental structure and interacts with organic molecules, such as collagen [3]. This interaction lightens the structure by breaking down these molecules through the action of free radicals and HP [3]. The bleaching efficacy of HP-based gels is well-established in the literature, with two sessions typically being sufficient to achieve the desired whitening results [8,45].

The results of the present study did not demonstrate significant benefits regarding the use of co-doped nanoparticles in bleaching gels. Although the literature suggests that incorporating these nanoparticles could potentially enhance the generation and longevity of ROS, promoting a more sustained interaction with the organic components of teeth and reducing pulp permeability [25–33], the findings of this study do not support these expectations. No relevant improvements were observed in bleaching efficacy, and the anticipated benefit of nanoparticles in accelerating the bleaching process or enhancing final efficacy was not observed. Groups using the gel, whether combined with violet light or not, showed no significant differences in bleaching time or final outcome. Additionally, violet light alone did not produce clinically relevant efficacy compared to the other groups. While some studies reported positive results for certain evaluations, recent research suggests that light is attenuated with just 1 mm of enamel, indicating a more superficial effect [37]. These results indicate that, despite the theoretical potential for optimizing photocatalysis processes, the practical

Table 3
Absolute risk of tooth sensitivity for all experimental groups, along with absolute and relative risk and 95 % confidence interval (CIs).

Protocols	Number of participants with tooth sensitivity		Absolut Risk (95 % CI)*	Relative Risk (95 % CI)**
	YES	NO		
BG+VIOL	8	14	36 (19 to 57) A	0.66 (0.34 to 1.30)
VIOL	7	15	32 (16 to 53) A	0.58 (0.28 to 1.19)
BG	14	8	63 (42 to 80) A	

* Risks identified with same letters are statistically similar; Chi-square test ($p > 0.13$).
** Compared with BG protocol.

Table 4
Intensity of tooth sensitivity (worst-case scenario) measured using the Numeric Rating Scale (NRS) and Visual Analog Scale (VAS), including median and interquartile range (NRS) and means and standard deviations (VAS) for each tested group.

	VIOL	BG	BG+VIOL	p-value
NRS (0–4)	0 (0–2)	0 (0–2)	0 (0–2)	0.48*
VAS (1–10)	0.33 ± 0.71	0.60 ± 0.82	0.89 ± 1.50	0.22**

Abbreviations: VAS – Visual Analogue Scale; NRS – Numerical Rating Scale.
* Kruskal-Wallis;.
** One-way ANOVA.

application of co-doped nanoparticles still lacks concrete evidence to justify their widespread clinical adoption, highlighting the need for further investigations to better understand the factors influencing their performance.

This study used two subjective evaluation methods (Vita Classical and Vita Bleachedguide scales) and three objective methods (using L*, a*, b* coordinates obtained with a digital spectrophotometer). CIELab is important because it is the most commonly used and oldest color evaluation method, [41] making it valuable for comparison with other studies [9] and future systematic reviews. CIEDE 2000 represents an evolution of CIELab [42], incorporating perceptual corrections that are more aligned with human eye [46].

Finally, the proposed method for evaluating color change in dental bleaching procedures, using the WI_D [43], stands out for its precision and direct correlation with human visual perception of whiteness [43]. Specific assessment of dental bleaching while eliminating interferences from chromatic components [43]. Psychophysical studies have shown that WI_D outperforms traditional indices in detecting color changes, due to its stronger correlation with visual perception and lower error rates [43]. Furthermore, the method establishes perceptibility and acceptability thresholds [44], allowing dental professionals to objectively identify the effectiveness and aesthetic satisfaction of bleaching treatments. As a linear formula index, it can be easily integrated into electronic instruments, eliminating subjective factors and standardizing color measurements [43]. Validated under both laboratory and clinical conditions, WI_D proves to be an effective and reliable tool for monitoring and validating dental bleaching procedures, ensuring greater precision in results.

Participants in the groups using the bleaching gel showed bleaching results beyond the acceptability limits for the three evaluation tools ($\Delta E_{ab} > 2.7$, $\Delta E_{00} > 1.8$, and $\Delta WI_D > 2.9$)[36, 44], indicating efficacy [47]. However, the group that used only violet light fell below these limits [36,44]. The literature indicates that few studies used WI_D when investigating violet light [19,21], but it appears to provide more precise results regarding bleaching efficacy [19,21], confirming the inefficacy of using violet light alone.

As reported, HP penetration in the groups subjected to bleaching agents is not restricted to hard tissues; it can potentially reach the pulp, causing inflammatory processes and TS, which is a common adverse effect of dental bleaching [3,4,48], as observed in the group BG in the present study. However, interesting results were noted for the group BG+VIOL. Despite this group receiving the bleaching gel, participants who underwent bleaching with the BG+VIOL experienced a lower risk of TS compared to those using the BG. As previously observed, the application of violet light increases the temperature of the gel on the tooth surface [4,30,49–53]. This elevated temperature can accelerate the release of HP while simultaneously leading to the degradation of the HP available for reaction. In fact, Vardasca et al. [4] reported that the application of violet light on 6 % HP resulted in a significant degradation, reducing the final concentration available for reaction on the tooth surface and, consequently, its overall availability. Additionally, the amount of HP in the pulp chamber decreased to one-third compared to the use of the bleaching gel alone. This finding indicates that the use of violet light during the application of HP is directly related to its degradation and helps to explain the lower TS observed in the group BG+VIOL.

However, VIOL does not pose a high risk of TS, as there is no oxidizing agent reaching the pulp. Nonetheless, some cases of TS have been reported, which may be associated with temperature changes caused by violet light [4,30,49–53]. Interestingly, when evaluating the intensity of TS, both groups demonstrated low levels, indicating that the conventional bleaching technique achieved similar bleaching efficacy and low TS intensity comparable to the group that did not use light.

In-office bleaching protocols have gained popularity because they allow the dentist full control over the treatment and typically report lower TS intensity is reported, as demonstrated by other studies [12]. The study explored new protocols involving violet light to determine its potential benefits. However, bleaching gel alone remains effective for dental bleaching. While more sessions may be required with a 6 % HP concentration compared to the more commonly 35 % HP concentration [10,11,38], the advantage is lower intensity of TS.

This study has several limitations that should be acknowledged. First, the use of only a single commercial concentration of HP (6 %) restricts the ability to assess the efficacy of violet light when combined with higher concentrations of bleaching agents. Additionally, only one specific violet light source was utilized. Given the variations in power, wavelength, and energy output among different violet light devices, this limits the generalizability of the study's findings to other violet light systems. Future studies should explore a broader range of HP concentrations and test multiple light sources to better understand their combined effects on bleaching outcomes.

5. Conclusion

Using only violet light reduced the risk of tooth sensitivitty but did not improve bleaching efficacy. However, combining violet light with bleaching gel with low-concentration HP nanoparticulate photocatalyst gel achieved similar efficacy while being less likely to cause tooth sensitivity compared to using only bleaching gel.

CRediT authorship contribution statement

Gustavo Garcia Castro: Writing – original draft, Validation, Methodology, Investigation, Conceptualization. **Palena Araújo Pinto:** Writing – original draft, Methodology, Investigation, Conceptualization. **Michael Willian Favoreto:** Writing – original draft, Supervision, Methodology, Conceptualization. **Alessandra Reis:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Maria Viviana-Mora:** Writing – original draft, Methodology, Data curation. **Rita de Cássia Mendonça de Miranda:** Writing – original draft, Methodology, Conceptualization. **Andres Felipe Milan Cardenas:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Alessandro D. Loguercio:** Conceptualization, Formal analysis, Supervision, Writing – original draft, Writing – review & editing. **Rudys Rodolfo de Jesus Tavarez:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization.

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